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A distorted radio shell in the young supernova SN 1986J

M.A. Pérez-Torres,[1] A. Alberdi,[2] J.M. Marcaide,[3] J.C. Guirado,[3] L. Lara,[2]
F. Mantovani,[1] E. Ros,[4] K. Weiler[5]

[1] *Istituto di Radioastronomia – CNR, Via P. Gobetti 101, I-40129 Bologna, Italy*
[2] *Instituto de Astrofísica de Andalucía, CSIC, Apdo. Correos 3004, E-18080 Granada, Spain*
[3] *Departamento de Astronomía y Astrofísica, Universidad de Valencia, E-46100 Burjassot, Spain*
[4] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany*
[5] *Remote Sensing Division, Naval Research Laboratory, Code 7213, Washington, DC 20375-5320, US*

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ABSTRACT

We report here on 5 GHz global very-long-baseline interferometry (VLBI) observations of SN 1986J, 16 yr after its explosion. We obtained a high-resolution image of the supernova, which shows a distorted shell of radio emission, indicative of a deformation of the shock front. The angular size of the shell is ~ 4.7 mas, corresponding to a linear size of $\sim 6.8 \times 10^{17}$ cm for a distance of 9.6 Mpc to NGC 891. The average speed of the shell has decreased from $\sim$7400 km s^{-1} in 1988.74 down to about 6300 km s^{-1} in 1999.14, indicative of a mild deceleration in the expansion of SN 1986J. Assuming a standard density profile for the progenitor wind ($\rho_{\rm cs} \propto r^{-s}, s = 2$), the swept-up mass by the shock front is $\sim$2.2 M$_\odot$. This large swept-up mass, coupled with the mild deceleration suffered by the supernova, suggests that the mass of the hydrogen-rich envelope ejected at explosion was $\gtrsim$ 12 M$_\odot$. Thus, the supernova progenitor must have kept intact most of its hydrogen-rich envelope by the time of explosion, which favours a single, massive star progenitor scenario. We find a flux density for SN 1986J of $\sim$7.2 mJy at the observing frequency of 5 GHz, which results in a radio luminosity of $\sim 1.4 \times 10^{37}$ erg s^{-1} for the frequency range 10^7–10^{10} Hz ($\alpha = -0.69; S_\nu \propto \nu^\alpha$). We detect four bright knots that delineate the shell structure, and an absolute minimum of emission, which we tentatively identify with the centre of the supernova explosion. If this is the case, SN 1986J has then suffered an asymmetric expansion. We suggest that this asymmetry is due to the collision of the supernova ejecta with an anisotropic, clumpy (or filamentary) medium.

Key words: Techniques: interferometric – supernovae: individual: SN 1986J – ISM: supernova remnants - Radio continuum: stars – Galaxies: individual: NGC 891

1 INTRODUCTION

Type II supernovae (SNe) are associated with massive stars that have expelled slow, dense winds during their supergiant phase. The stellar explosion drives a shock into this wind, at speeds as high as 20000 km s^{-1} and temperatures of $\sim 10^9$ K. In addition, a reverse shock propagates back into the stellar envelope at speeds of 500-1000 km s^{-1} relative to the expanding ejecta. This is the so-called standard interaction model (hereafter SIM; Chevalier 1982, Nadyozhin 1985), and radio, optical, and X-ray emission from Type II supernovae have been usually interpreted within this model. The outgoing shock forms a high-energy-density shell that is responsible for the production of synchrotron radio emission, while the reverse shock accounts for the optical and soft X-ray emission.

SN 1986J in NGC 891 is one of the most radio luminous SNe ever discovered. Indeed, at a distance of $\approx$ 9.6 Mpc (Tully 1998), it had a peak luminosity at 5 GHz about 8 and 13 times greater than SN 1979C and SN 1993J, respectively. The precise date of its explosion is not known, but on the basis of the available radio and optical data SN 1986J was estimated to have exploded around the end of 1982, or the beginning of 1983 (Rupen et al. 1987, Chevalier 1987, Weiler, Panagia & Sramek 1990). Based upon its large radio luminosity, Weiler, Panagia, & Sramek (1990) suggested that the progenitor star was probably a red giant with a main-sequence mass of 20 – 30 M$_\odot$ that had lost material rapidly ($\dot{\rm M} \gtrsim 2 \times 10^{-4}$ M$_\odot$ yr^{-1}) in a dense stellar wind. VLBI observations by Bartel et al. (1991) showed that the radio structure of SN1986J had the form of a shell, in agree-

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ment with expectations from the SIM model, with the minimum of emission located approximately at its center.

SN 1986J is peculiar in several respects. (i) Bartel et al. (1991) showed the presence of protrusions in the brightness distribution of the supernova. This finding was interpreted as evidence of deviation from spherical symmetry. Another supernova for which considerable asymmetry in its radio structure has been found is SN1987A (Gaensler et al. 1997, and references therein). Those cases contrast with the remarkable spherically symmetric expansion observed for the radio shell of SN 1993J (Marcaide et al. 1995, 1997; Bartel et al. 2000); (ii) the radio light curves for SN 1986J were not well fitted within the SIM for radio supernovae, which led Weiler et al. (1990) to invoke the existence of a mixed medium (thermal absorbers and non-thermal emitters), or significant filamentation in the circumstellar medium; (iii) optical spectra obtained in 1986 (Rupen et al. 1987) and in 1989 (Leibundgut et al. 1991) showed optical narrow lines with FWHM ≈ 500 - $700\,\mathrm{km\,s^{-1}}$. In the SIM, the optical and X-ray emission arise in the reverse shock, which moves with a speed close to that of the forward shock, i.e., several thousands $\mathrm{km\,s^{-1}}$. Since the optical velocities are far lower than those determined from VLBI (radio) observations at similar epochs, these narrow lines question the validity of the SIM to successfully explain the observed optical and X-ray emission from SN 1986J. Chugai (1993) proposed a different model which overcomes the problems of the SIM and seems plausible for SN 1986J. In his model, the supernova envelope is not colliding with a smooth distribution of wind material, but with a clumpy one, and the bulk of the observed X-rays originates in the shocked dense wind clumps. Therefore, the narrow-line ($\Delta v \sim 500\,\mathrm{km\,s^{-1}}$) material is not directly related to the shock wave (which moves at much higher speeds), but to the speed of the shock-excited dense clouds. More recently, Chugai & Belous (1999) have shown that the evolution of the radio light curves of SN1986J can be well interpreted by free-free absorption in a clumpy wind. The possible presence of clumps of radio absorbing plasma is also consistent with the proposal by Weiler et al. (1990) for a filamentary structure in the circumstellar medium.

Unfortunately, VLBI observations of SN 1986J have been so scarce since its explosion that only one high-resolution radio image for SN 1986J exists (Bartel et al. 1991). In this paper, we use very sensitive 5 GHz global VLBI observations taken on 21 February 1999 to obtain the second high-resolution radio image of SN 1986J, 16 yr after its explosion. We present a brief report of the VLBI observations in section 2, present and discuss our results in section 3, and summarize our conclusions in section 4.

2 VLBI OBSERVATIONS AND IMAGE PROCESSING

We used archival global VLBI data for SN 1986J. The supernova was observed at a frequency of 5 GHz from 17:00 UT on 21 February 1999 to 04:50 UT on 22 February 1999, using a very sensitive VLBI array that included the following antennas (diameter, location): The whole VLBA (25m, 10 identical antennas across the US), phased-VLA (130m-equivalent, NM, US), Effelsberg (100m, Germany), Medicina and Noto (32m each, Italy), and Onsala (20m, Sweden). The telescopes received both left- and right-hand circular polarizations (LCP and RCP) which, after correlation, were combined to obtain the total intensity mage presented in this paper. Effelsberg had technical problems (damaged gear) and thus could not take part in the observations. Onsala only recorded in LCP mode, and therefore its data were not used to obtain our total intensity VLBI image.

The observations were made with a bandwidth of 64 MHz. The data were correlated at the VLBA Correlator of the National Radio Astronomy Observatory (NRAO) in Socorro (NM, US). The correlator used a pre-averaging time of 3 s. Since SN 1986J was expected to be very faint, at a level of a few mJy, the observations were carried out in phase-reference mode. SN 1986J and the nearby ICRF source, 3C 66A, were alternately observed during the 12-hr experiment. The observations consisted of ~ 120 s scans on SN1986J and of ~ 70 s scans on 3C 66A, plus a few additional seconds of antenna slew time to make a duty cycle of 190 s. 3C 66A was also observed as amplitude calibrator for SN 1986J. The source 3C 84 was observed as a fringe finder.

The correlator data were analyzed using the Astronomical Image Processing System (AIPS). The visibility amplitudes were calibrated using the system temperature and gain information provided for each telescope. The instrumental phase and delay offsets among the 8-MHz baseband converters in each antenna were corrected using a phase calibration determined from observations of 3C 84. The data for the calibrator 3C 66A were then fringe-fitted in a standard manner. We exported the 3C 66A data into the Caltech imaging program DIFMAP (Shepherd et al. 1995) for mapping purposes. 3C 66A showed a flux of ~ 0.95 Jy at 5 GHz, and displayed a one-sided core-jet structure at mas scales, with the jet extending southwards up to ~ 28 mas. The final source model obtained for 3C 66A was then included as an input model in a new fringe-fitting search for 3C 66A. In this way, the solutions obtained were structure-free. The phases, delays, and delay-rates determined for 3C 66A were then interpolated and applied to the source SN 1986J. The SN 1986J data were then transferred into the DIFMAP program. Standard self-calibration techniques and purely uniform weighting were used to achieve maximum resolution in the hybrid maps shown in Fig. 1.

We note two powerful aspects of the use of the phase-reference technique: (i) it effectively increases the integration time on a source from minutes to hours, thus allowing the detection and imaging of very faint objects (e.g. Beasley and Conway 1995), and (ii) it retains the positional information of SN 1986J with respect to the phase-reference source, 3C 66A, almost 1 degree apart. Indeed, a Fourier inversion of the SN 1986J data within DIFMAP, before applying any self-calibration, showed that the a priori position of SN 1986J used in the correlator ($\alpha = 02^{\mathrm{h}}22^{\mathrm{m}}31^{\mathrm{s}}.320$, $\delta = +42^{\circ}19'57''.282$; J2000.0) was off from the actual one by $\sim$17 mas in right ascension (westwards), and by $\sim$21 mas in declination (southwards). Therefore, phase-referencing proved to be also useful in providing further refinements in the precise coordinates of SN 1986J.

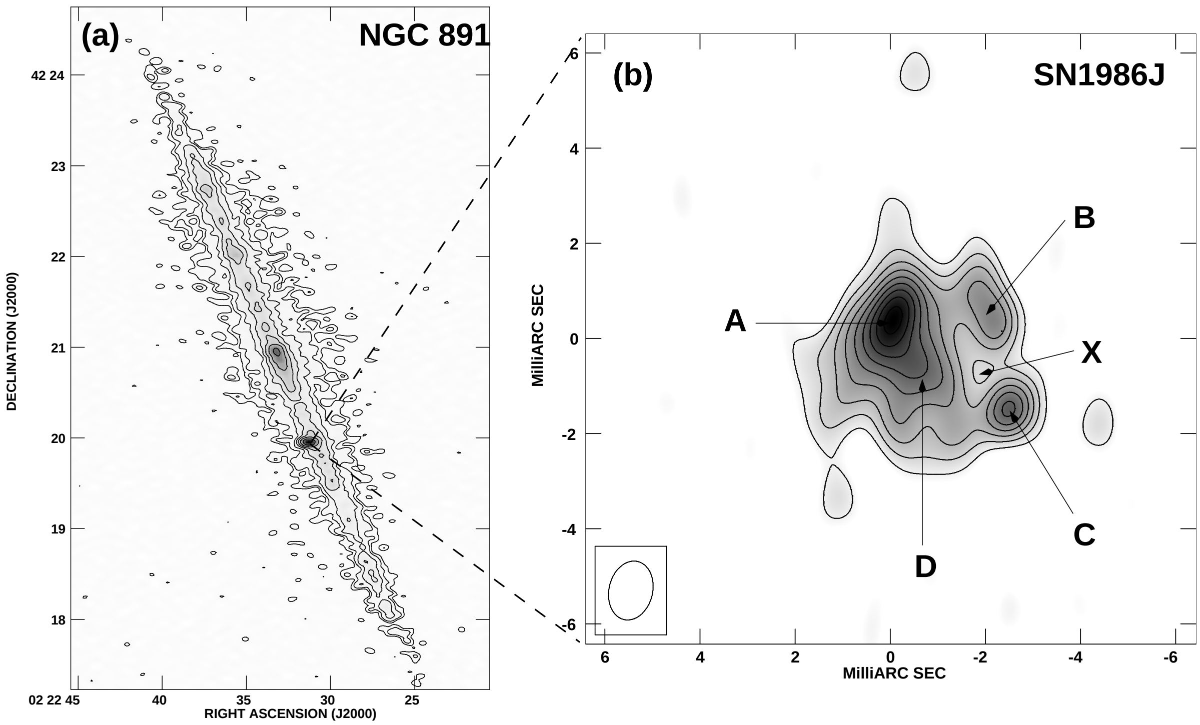

Figure 1. **(a)** Hybrid map of the galaxy NGC 891 and its supernova SN 1986J made with the Very Large Array (VLA) at the same frequency (5 GHz) and epoch of the global VLBI observations on February 21, 1999. The contours are (3,5,10,20,40,80,160,300) $\times$ 25 μJy beam^{-1}, the root-mean-square (rms) noise off-source. The peak of brightness of the map corresponds to the supernova and is $\sim$ 8.2 mJy beam^{-1}. The dimensions (full width at half maximum) of the restoring beam are 7.4 $\times$ 4.0 arcsec^2, with the beam's major axis oriented along a position angle of 88°. **(b)** Global Very-Long-Baseline Interferometry (VLBI) hybrid map of SN 1986J on February 21, 1999. The contours are (3,5,7,9,11,13,15,17,19) $\times$ 56 μJy beam^{-1}, the rms noise off-source. The peak of brightness of the map is 1.13 mJy beam^{-1} and the restoring beam (bottom left in the image) is 1.3 $\times$ 0.9 mas^2 at a position angle of -13°.4. In both panels, north is up and east is left.

3 RESULTS AND DISCUSSION

The only other available radio image of SN 1986J is that obtained by Bartel et al. (1991; hereafter B91) of 29 September 1988, at a frequency of 8.4 GHz. Our global VLBI image of 21 February 1999 was obtained at 5 GHz. The most remarkable thing in our image (panel (b) in Fig. 1) is the fact that the brightness distribution of SN 1986J still shows the form of a shell, even though more than 10 yr since the last observations have passed. However, the shell, definitely distorted and with strong asymmetries, shows changes in the brightness distribution between the two epochs.

3.1 Asymmetric shell morphology and protrusions in SN 1986J

We distinguish at least four bright features in the rim of the shell labeled A,B, C, and D in Fig. 1. The absolute minimum ($\sim$0.26 mJy beam^{-1}) of the shell brightness distribution is indicated by the X in panel (b). The flux densities and distances of the bright features A,B,C, and D from X are shown in Table 1. At a flux density of 1.13 mJy beam^{-1}, the corresponding brightness temperature of feature A is $\sim$ 1.8 $\times$ 10^7 K. Features B and C are local maxima with brightness temperatures of $\sim$1.0 and $\sim$1.2 $\times 10^7$ K, respectively. Component D is an extended feature in the AC direction. Therefore, its flux density and radial distance from X are just indicative.

The image by B91 showed several 'knots' along the rim of the shell of the supernova brightness distribution. The strongest knot was located northeast of the center, with a peak brightness temperature of $\sim$ 3 $\times$ 10^8 K. B91 also showed the presence of protrusions in the brightness distribution of the supernova, at a distance of $\sim$ 1.9 mas from the centre. We note that the radial distances to features A, B, and C in Fig. 1 are comparable to the radial distances to the protrusions observed by B91, and therefore one could be tempted to identify features A, B, and C with stationary clumps in the CSM of SN1986J. However, caution must be taken, since not only the position angles are different, but also our synthesized beam is significantly larger than that of B91. Our image also shows three spots outside the shell structure at contours above 3 times the rms noise off-source. These spots have distances and position angles with respect to X that are significantly different from those obtained by B91, and therefore do not correpond to the same physical features shown in B91. The peaks of these spots range from 0.23 to 0.25 mJy/beam, less than the minimum of emission within the shell. Therefore, they could be mere artifacts of the image reconstruction procedure, implying that the protrusions seen by B91 have disappeared during the period ranging from September 1988 to February 1999, and point-

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Table 1. Flux density and radial distance to X for the features shown in panel (b) of Fig. 1. The position of X is $\alpha = 02^{\rm h}\!.22^{\rm m}\!.31^{\rm s}\!.3214$, $\delta = 42^\circ\!.19'\!.57''\!.260$

	Flux mJy beam^{-1}	Radial distance (mas)
A	1.13	2.14
B	0.62	1.10
C	0.77	0.99
D	0.74	1.41

ing to a change in the density properties of the presupernova wind.

Our image also shows that the radio shell morphology of SN 1986J is asymmetric. The four bright features in Fig. 1 seem to delineate a highly distorted shell –whose minimum of emission is not at its centre– and are indicative of a significant deformation of the shock front. If the point X in panel (b) corresponds to the centre of the explosion, we obtain the angular radial distances shown in Table 1 for the knots in the shell of the supernova. It would appear then that the supernova has expanded more along the AC axis. In addition, the angular radial distance XA is more than twice the distance XC, indicative of a strong asymmetric expansion. We note, however, that our identification of X with the centre of the supernova explosion is not unique. In this respect, future phase-reference VLBI observations will be most useful, since this technique will allow a proper registration of the maps, thus permitting the identification of the centre of the explosion.

Nevertheless, most of the results presented and discussed below do not depend on the putative centre of the explosion. In particular, the brightness distribution of SN 1986J is clearly asymmetric, independent of the location of the centre of the explosion. How could such an asymmetric structure have arisen? Various models have been proposed to account for asymmetric morphologies in supernovae. Blondin, Lundqvist & Chevalier (1996) have suggested that an axisymmetric density distribution in the wind from a supernova progenitor leads to protrusions emerging along the symmetry axis. These authors find that for a power-law supernova density profile, the flow approaches a self-similar state in which the protrusion length is 2–4 times the radius of the shell, after $\sim$ 10 yr. They cite the supernova remnant 41.95+575 in M 82 as an example where such axisymmetric protrusions are likely to have emerged, but point out that their model is not compatible with the protrusions seen by B91 for SN 1986J. A case where considerable asymmetry in its overall structure has been observed is SN1987A. Gaensler et al. (1997) showed that the eastern and western regions of the SN1987A radio remnant were brighter than the northern and southern regions, and interpreted this as evidence for the shocked wind being axisymmetric in its shape and/or density distribution. From our image, it follows that an axisymmetric circumstellar interaction does not seem to apply for SN1986J. The protrusions outside the shell, on the other hand, could be formed by an asymmetric distribution in the wind similar to that invoked by Blondin et al. (1996), though not restricted to be axisymmetric. Other models that predict supernova aspherical morphologies include that of Khokhlov et al. (1999), which have modeled jet-induced explosions of core collapse supernovae. The end result is a highly aspherical supernova with two high-velocity jets of material moving in polar directions, and a slower moving, highly distorted ejecta containing most of the supernova material. A recent VLBI image of 41.95+975 by McDonald et al. (2001) reveals structure resembling that of a collimated outflow, as expected from the model by Khokhlov et al. (1999). Although in our case one could identify the brightest knots A and C with a collimated outflow, there is also strong emission in the almost perpendicular direction BD. In addition, all four knots seem well confined within the supernova shell. Therefore, the existence of two high-velocity, well collimated jets in SN 1986J seems unlikely. In the case of SN1987A, a directional anisotropy in the supernova explosion might be indicated by the fact that the eastern limb of SN1987A was brighter, and was also increasing in brightness more rapidly, than the western limb (Gaensler et al. 1997). Although such a directional anisotropy in SN1986J could explain the existence of feature A (which roughly corresponds to the strongest knot of emission seen by B91), it has difficulties in explaining the change in position angles for the other peaks, as well as the appearance of features B and D. We therefore favour an scenario where the strongly asymmetric brightness distribution of the SN 1986J shell structure is due to the collision of the supernova ejecta with a clumpy (Chugai 1993, Chugai & Belous 1999), or filamentary wind (Weiler et al. 1990). Our image gives support to this model, and shows that the clumpy, or filamentary wind must probably be inhomogeneous to produce a highly distorted shell.

3.2 Deceleration of the expanding shell

At a distance of 9.6 Mpc (Tully 1998), 1 mas corresponds to a linear size of $\sim 1.4 \times 10^{17}$ cm ≈ 0.05 pc. Based on 8.4 GHz VLBI observations, B91 found an angular size of $\sim$3.7 mas ($\approx 5.3 \times 10^{17}$ cm ≈ 0.17 pc) for the shell of SN 1986J, 5.74 yr after its explosion (assuming it took place on 1983.0). The corresponding mean linear velocity would then be $\sim$14700 km s^{-1} for the first 5.74 yr. However, this velocity applies only to the protrusions found by B91, not to the shell. Indeed, the velocities reported in B91 were calculated for the protrusions, and assuming that these originated in the centre at the time of the explosion. These authors also pointed out that the protrusions extended from the centre to twice the radius of the shell, i.e., the protrusions were *outside* the shell. Therefore, a value of $\sim$1.85 mas ($\approx 2.7 \times 10^{17}$ cm ≈ 0.09 pc) for the angular size of the shell of SN 1986J at epoch 1988.74 is indicated, and a mean linear velocity of the radio shell of $\sim$7400 km s^{-1} is more appropriate to characterize the first 5.74 yr of the expansion of SN 1986J, as has been previously noticed by Chevalier (1998) and Houck et al. (1998). Chevalier (1998) also pointed out that such a velocity at roughly the time of the peak flux is evidence against the synchrotron self-absorption mechanism acting in SN 1986J.

The angular size of the supernova (at the 5-rms noise level) along the AC direction in Fig.1 is $\theta \approx 4.7 \pm 0.3$ mas, equivalent to $\approx 6.8 \times 10^{17}$ cm ≈ 0.22 pc. Combining this angular size measurement with that obtained by Bartel et al. (1991) for epoch 1988.74 ($\theta \approx 1.85$ mas), we then obtain a mean angular expansion velocity of the shell between 29

September 1988 (1988.74) and 21 February 1999 (1999.14) of $\approx 0.14\,\mathrm{mas\,yr^{-1}}$, which corresponds to a linear velocity of $\sim 6300\,\mathrm{km\,s^{-1}}$. If we assume that SN 1986J freely expanded for the first 5.74 yr of its life ($r \propto t^m, m = 1$) and then started to decelerate, the expansion between the two epochs of VLBI observations is characterized by $m = 0.90 \pm 0.06$. This is a mild deceleration, and contrasts with the case of several other supernovae, for which a strong deceleration has been measured (SN1979C: Marcaide et al. 2002; SN1987A: Staveley-Smith et al. 1993, Gaensler et al. 1997; SN1993J: Marcaide et al. 1997, Bartel et al. 2000). Thus, the angular size that we obtain for the shell seems consistent with the conclusion that the bulk of the shell structure expanded for the first 5.74 yr at speeds smaller than $\sim 15000\,\mathrm{km\ s^{-1}}$ (see above and Chevalier 1998).

For a standard presupernova wind velocity, v_w=10 $\mathrm{km\ s^{-1}}$, the linear size of SN 1986J at epoch t=16.14 yr implies that we are sampling the progenitor wind about 11000 yr prior to its explosion. Since the mass loss rate of SN 1986J seems to have been $\gtrsim 2 \times 10^{-4}\ \mathrm{M_\odot\,yr^{-1}}$ (Weiler, Panagia & Sramek 1990), the swept-up mass must have been $\mathrm{M_{sw}} \approx 2.2\,\mathrm{M_\odot}$, and the thermal electron density $\sim 8\times 10^3\,\mathrm{cm^{-3}}$ (for a standard density profile of the progenitor wind, $\rho_{\rm cs} \propto r^{-2}$). Since the expansion of the supernova has not decelerated significantly between the two VLBI observations, it follows that the swept-up mass by the shock front must be much less than the mass of the ejected hydrogen-rich envelope, $\mathrm{M_{env}}$, as otherwise we should have observed a much stronger deceleration. In fact, momentum conservation implies that $\mathrm{M_{env}} \gtrsim 12\ \mathrm{M_\odot}$, significantly larger than $\mathrm{M_{sw}}$. If the hydrogen-rich mass envelope was as high as 12 $\mathrm{M_\odot}$, this is a hint that the progenitor of SN 1986J was probably a single, massive Red Super Giant (as previously suggested by Weiler et al. 1990), which lost mass rapidly, but managed to keep intact most of its hydrogen-rich envelope by the time of explosion. This result contrasts with the cases of SN 1993J and SN 1979C, whose hydrogen-rich envelopes had masses of 0.2–0.4 $\mathrm{M_\odot}$(Woosley et al. 1994, Houck & Fransson 1996) and $\lesssim 0.9\ \mathrm{M_\odot}$ (Marcaide et al. 2002), and whose progenitor stars were part of binary systems.

3.3 Total energy and magnetic field of SN 1986J

Since the radio emission is of synchrotron origin, we can estimate a minimum total energy (in magnetic fields, electrons, and heavy particles) and a minimum magnetic field for SN 1986J. If we assume equipartition (magnetic field energy is approximately equal to the total particle energy), then the minimum total energy is (Pacholczyk 1970) $E^{\rm (tot)}_{\rm min} = c_{13}\,(1+k)^{4/7}\,\phi^{3/7}\,R^{9/7}\,L^{4/7}$, where L is the radio luminosity of the source, R is a characteristic size, c_{13} is a slowly-dependent function of the spectral index, α, ϕ is the fraction of the supernova's volume occupied by the magnetic field and by the relativistic particles (filling factor), and k is the ratio of the (total) heavy particle energy to the electron energy. This ratio depends on the mechanism that generates the relativistic electrons, ranging from $k \approx 1$ up to $k = m_p/m_e \approx 2000$, where m_p and m_e are the proton and electron mass, respectively.

Based on snapshot VLA observations of SN 1986J carried out on 13 June 1999 (Weiler, private communication), we determined an spectral index of $\alpha = -0.69 \pm 0.06$ ($S_\nu \propto \nu^\alpha$) between 1.6 and 8.5 GHz. This value is very close to $\alpha = -0.67$ obtained by B91, and is a typical value for supernovae that are in the optically thin radio regime. With $\alpha = -0.69$ and $S_{\rm 4.9GHz} = 7.2$ mJy from our observations, we obtain a radio luminosity $L_\nu \approx 1.38 \times 10^{37} (D/9.6\mathrm{Mpc})$ $\mathrm{erg\,s^{-1}}$ for the frequency range 10^7–10^{10} Hz. The value of the function c_{13} is approximately 2.39×10^4 (for $\alpha = -0.69$, and ν_1 and ν_2 equal to 10^7 and 10^{10} Hz, respectively). The filling factor, ϕ, is by definition ≤ 1. In the case of supernova SN 1993J, Marcaide et al. (1995a, 1995b, 1997) showed that the radio emitting shell of SN 1993J had a width, $\Delta R \approx 0.3\,R_{\rm out}$, where $R_{\rm out}$ is the outer shell radius, and therefore $\phi \approx 0.66$. As the characteristic size for SN 1986J, we will take half the largest diameter of the shell, $\theta = 2.35$ mas, which corresponds to a linear size of $R = D\cdot\theta \approx 3.4\times10^{17}$cm. With these values, the minimum total energy is then

$$E^{\rm (tot)}_{\rm min} \approx 1.13 \times 10^{48}\,(1+k)^{4/7}\,\phi_{0.66}^{3/7}\,\theta_{2.35}^{9/7}\,D_{9.6}^{14/7}\ \mathrm{erg}$$

where $\phi_{0.66} = (\phi/0.66)$ $\theta_{2.35} = (\theta/2.35\,\mathrm{mas})$, and $D_{9.6} = (D/9.6\mathrm{Mpc})$. The value of the magnetic field that yields $E^{\rm (min)}_{\rm tot}$ is then equal to

$$B_{\rm min} \approx 10.6\,(1+k)^{2/7}\,\phi_{0.66}^{-2/7}\,\theta_{2.35}^{-6/7}\,D_{9.6}^{-2/7}\mathrm{mG}$$

Since $1 \le k \le 2000$, $E^{\rm (tot)}_{\rm min}$ can have values between $\sim 2\times10^{48}$ and $\sim 9\times10^{49}$erg, while the corresponding values of the magnetic field can lie between ~ 13 and ~ 93 mG (for $\phi = 0.66$ and $D = 9.6$Mpc). These values of the magnetic field for SN 1986J are in agreement with, e.g., those obtained for SN 1993J at similar radii. For example, Pérez-Torres, Alberdi, and Marcaide (2001) showed that $B \approx 0.58\,(r/3\times10^{16}\,\mathrm{cm})^{-1}$ G, which results in a value of ~ 50 mG for a radius of 3.4×10^{17} cm. Since it is very unlikely that the magnetic field energy density in the wind is larger than its kinetic energy density, i.e., $B^2/8\pi \le \rho v_{\rm w}^2/2$, we can then obtain an upper limit for the magnetic field in the circumstellar wind of SN 1986J:

$$B_{\rm cs} \lesssim (\dot{\mathrm{M}}\,v_w)^{1/2}\,r^{-1} \approx 0.78\,(\dot{\mathrm{M}}_{-4}\,v_{10})^{1/2}\,r_{17}^{-1}\ \mathrm{mG}$$

where $\dot{\mathrm{M}}_{-4} = \dot{\mathrm{M}}/10^{-4}\ \mathrm{M_\odot\,yr^{-1}}$, $v_{10} = v_w/10\ \mathrm{km\ s^{-1}}$, $r_{17} = r/10^{17}$ cm, and we have assumed a standard wind density profile. For SN 1986J, $\dot{\mathrm{M}} = 2\times10^{-4}\ \mathrm{M_\odot\,yr^{-1}}$ and $r = 3.4\times10^{17}$ cm, and we obtain $B_{\rm cs} \lesssim 0.32$ mG. These arguments suggest that the magnetic field in the shell of SN 1986J is in the range 13–93 mG, or about 40 to 300 times the magnetic field in the circumstellar wind. Since a strong shock yields a fourfold increase in the particle density, the post-shock magnetic field is also fourfold increased. Hence, compression alone of the circumstellar wind magnetic field cannot account for the large magnetic fields existing in SN 1986J, and other field amplification mechanisms are needed to be invoked, e.g., turbulent amplification (Chevalier 1982; Chevalier & Blondin 1995). The same conclusion was reached for the case of SN 1993J (Fransson & Björnsson 1998, Pérez-Torres, Alberdi & Marcaide 2001), where magnetic field amplification factors ~ 100 were found to be necessary.

4 SUMMARY

We used 5 GHz global VLBI observations of SN 1986J taken on 21 February 1999 to obtain a high-resolution radio image of the supernova about 16 yr after its explosion (assumed to have occurred on 1983.0). Our main results can be summarized as follows:

(i) The radio structure of SN 1986J is shell-like, even after more than 16 yr since its explosion. However, the shell is highly distorted, indicative of a strong deformation of the shock front.

(ii) Assuming that the shell seen in our 1999.14 image corresponds to the shell in the 1988.74 image, the expansion of SN 1986J has decelerated from $\sim$7,400 km s^{-1} down to $\sim$6,300 km s^{-1}. This mild deceleration can be characterized by a power-law ($r \propto t^m$) with a deceleration parameter $m = 0.90 \pm 0.06$. Since the swept-up mass must be ≈ 2.2 M$_\odot$ (for $\dot{\rm M} = 2 \times 10^{-4}$ M$_\odot$ yr^{-1} and $v_w = 10$ km s^{-1}), this mild deceleration seems to indicate a mass of the hydrogen-rich envelope ejected at explosion of $\gtrsim 12$ M$_\odot$. In this case, the supernova progenitor kept almost intact its hydrogen-rich envelope, in spite of its strong mass-loss wind rate, and is a strong hint that SN 1986J went off in a single, massive star scenario.

(iii) We show that the brightness distribution in the shell is strongly asymmetric, and suggest that the most likely scenario for its origin is the collision of the supernova envelope with a clumpy, or filamentary, anisotropic wind. However, we cannot exclude that other mechanisms, such as a directional anisotropy in the supernova explosion, may also play a role in shaping the radio emitting structure of SN1986J. We detect three emission spots at the 3-rms noise level outside the shell. Though these spots could be protrusions alike those detected by Bartel et al. (1991), we suggest that they are mere artifacts of the image reconstruction procedure.

(iv) The radio flux of SN 1986J is $\sim$ 7 mJy, which results in a luminosity of about 1.4×10^{37} erg s^{-1}. By assuming equipartition between fields and particles, we estimate a minimum energy for the supernova shell in the range $E_{\rm min}^{\rm (tot)} \approx 0.2$–$9 \times 10^{49}$ erg, which corresponds to a minimum magnetic field of $B_{\rm min} \approx 13$–93 mG. We find that the average magnetic field in the circumstellar wind of SN 1986J is $B_{\rm cs} \lesssim 0.32$ mG. Therefore, powerful amplification mechanisms (e.g. turbulence) should be acting in SN 1986J, since compression alone of the circumstellar field cannot account for the magnetic fields existing in the supernova shell.

The high-resolution radio image of SN 1986J presented here shows that VLBI is a very powerful technique for investigating the interaction of supernovae, because it allows to directly image the emission from the interaction region (supernova ejecta and shocked wind). Supernova SN 1986J belongs to the rare group of radio supernovae that permit their follow-up with VLBI. Further high-resolution, sensitive VLBI observations of SN 1986J are necessary to provide us with a more detailed view of its evolution and interaction with the circumstellar medium. The use of phase-referencing will be mandatory, since this technique will not only ensure the detection of the supernova, but will also allow a proper registration of the images for all epochs. This registration will likely permit the unambiguous identification of the centre of the explosion. Moreover, such observations would also allow to shed further light on the apparent asymmetric pre-supernova wind of SN1986J, obtain a better determination of the deceleration parameter, and definitively confirm, or reject, the protrusions outside the supernova shell structure we have marginally detected here.

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